STUDY ON PERFORMANCE OF SOLAR DRYER WITH PHASE CHANGE MATERIAL (PCM) FOR AGRO PRODUCTS

A SYNOPSIS

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1. INTRODUCTION

Drying is one of the most widely recognized post-harvest unit activities for the preservation of farming items. Drying is a process of removing the moisture in the food, which has gained much recognition in agricultural crop-processing industries [1]. It helps to avoid the microbial action produced due to high MC and subsequently extends the timeframe of realistic usability of the item [2]. The method of drying crops needs to be appropriately selected to reduce the spoilage of food items, increase the final product quality and lessen the losses during storage. The hot air of temperature varies between 45 – 60 ℃ is essential to eliminate the water content from crops to safeguard good output quality [3,4].

The drying of vegetables and crops is one of the crucial processes that improve the usability of the products. Since drying requires high energy, different drying methods were explored to decrease energy utilization and increase drying efficiency [5]. With the increasing energy demand, the environmental effect of fossil fuel consumption, and mounting concerns of higher fuel costs, solar-powered energy poses an affordable option that does not significantly contribute to CO_2 and CO discharges and other contaminants. The sun is an indispensable source of obtainable energy (i.e., solar energy) for life on Earth [6].

solar energy has been explored as an alternate source of energy. The energy from the sun is clean, plentiful, and non-polluting [7]. The recent advancement in utilizing solar power has developed a widespread interest in several applications like drying, heating, cooling, and purifying. The use of solar energy can be mainly considered into two groups-electrical and thermal applications. The solar thermal system has been conventionally used in the farming sector to preserve vegetables, fruits, grains, etc. It is considered to be economical and generally familiar among the agricultural community; but, it is relatively less used in the manufacturing sector [8].

There are several solar drying systems: direct sun drying, direct solar drying, indirect type solar drying, and mixed-mode solar drying, cabinet solar drying, solar greenhouse drying and hybrid solar drying [9]. Among all available drying systems, Open drying is one of the simplest and traditional techniques employed to safeguard agro-food products and avoid loss of crop quality [10,11].

Open sun drying is the conventional and most adopted technique to dry and preserve farming products like grains, fruits, and vegetables in most countries [12,13]. The open sun drying method is adopted to preserve food products from spoiling in agro-

processing industries in many developing countries. However, this drying method under aggressive climate conditions leads to severe losses in the quantity and quality of the dried product [14,15]. For example, in open sun drying, the exposure to the sun is inconsistent from the period before noon to sunset, and when directly exposed to sunlight, the essential oil compounds are not completely reduced while the exposure affects the required colour, texture, and fragrance of the food products [16]. Besides, the open environment may expose the products to dust particles, insects, flies, wind, humidification at night, affecting the quality of the dried products and may subsequently affect the market value of the raw materials and final product [17].

The limitations of traditional drying can be overcome by selecting an efficient drying system. The requirement for high fuel or power to run the drying system has encouraged sunlight-based drying systems, particularly during reap and harvest seasons [18]. Solar energy for crop drying is harmless to the ecosystem and viable in most emerging countries [19]. The solar drying method is quicker, economically viable than mechanized dryers, hygienic, and more efficient than open-sun drying and the dried items exhibit an improved color and surface texture [20].

Compared to other drying methods, the solar dryer saves a lot of energy and obtains a better-quality food product. Solar drying is an evolving technology, which involves the utilization of solar energy for drying agricultural crops [21].

2. LITERATURE SURVEY

Solar dryer can be used for farmers to dry the agro products during off sunshine hours. Solar dryers will reduce the use of traditional electrical and fossil fuels, thereby reducing environmental issues caused by their use. The thermal performance of the solar dryer was improved by absorbing the high solar radiation Chauhan et al. [22]. Solar dryer was designed with sensor to control the drying environment. The system was entirely powered by solar energy, which was used in both thermal and electrical effects. Thermal energy was stored in paraffin wax, while electrical energy was stored in a solar battery. This system was designed with a capacity of 10-15 kg with 6 trays and maintained a temperature of 55-60 °C Devi et al. [23]. Drying air mass flow rate, surrounding air temperature, solar radiation, relative humidity, MC must be considered when designing an efficient solar dryer Le et al. [24]. The solar dryer performance can be evaluated by considering the following parameters like moisture removal rate, moisture reduction, drying time Nukulwar et al. [25].

The air inlet area of the dryer was found to have a significant effect on the dryer's performance. The dryer's performance improved when the air inlet area was increased, and vice versa Montero et al. [26]. It has been demonstrated that an increase in radiation causes an increase in the temperature of the chamber for a constant air flow, whereas an increase in air flow implies a decrease in the temperature of the chamber for a constant value of solar radiation. For ambient temperature 30.5 °C, the operating temperature of the dryer was 74.5 °C and the mass of water removal in vegetable was 199.9g in the solar dryer Shalaby and Bek [27]. The drying chamber maintains a maximum temperature upto 50-60 °C. Chavan et al. [28]. When compared to open sun drying, they noted that the dryer saved 65% of the total drying time. The quality of the solar dryer dried product is better when compared to open sun dry. The developed dryer's payback period was determined to be 1.3 years Malakar et al. [29].

3. RESEARCH GAP:

- Limited experimental works found in the literature comparison between conventional solar dryer with open drying.
- Also, very fewer studies available on the fabrication of solar dryer using PCM in India.
- Very few reports available about PCM usage in solar dryer for drying to reduce the spoilage of agro products and to reduce the drying time.
- Usage of microencapsulated PCM in the solar dryer is minimum.
- No works available regarding quantity of PCM.

4. OBJECTIVES

- To fabricate PCM solar dryer with suitable dimensions to demonstrate the effect of reducing the drying time.
- To identify the suitable PCM for drying crops after comprehending the concept.
- To measure the impact of PCM on thermal characteristics of drying the agro products
- To measure the impact of Micro and macro PCM on thermal characteristics of drying the agro products

5. METHODOLOGY

The methodology followed in the present research work is shown in the Figure

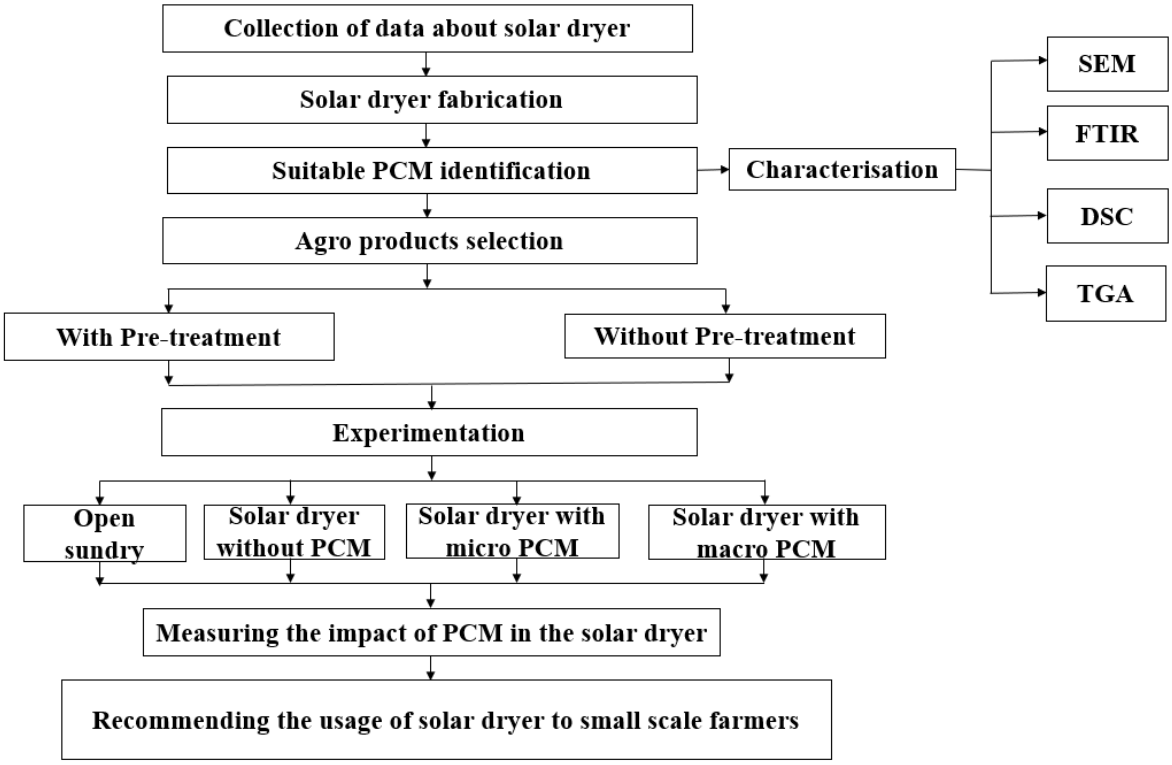

Figure 1 Research Methodology

ORGANIZATION OF THESIS

Chapter 1: This chapter labels the basic about solar drying, classification of solar drying. It also describes about PCM, classification of PCM, selected agro products and quality of dried agro products.

Chapter 2: In the next chapter, a thorough literature review about solar dryer, solar dryer integrated with PCM, natural and forced convection solar dryer, quality of the dried product was carried out, the research gap, objectives and methodology of the research work are presented.

Chapter 3: This chapter labels the materials and methodology of this research work. These chapter includes the experimental details and testing methods for the dried sample.

A direct type normal convection solar dryer (700 × 300 × 300 mm^3) was manufactured and mounted at Kalasalingam Academy of Research and Education, Tamilnadu (India). The latitude and longitude of the solar dryer located is about 9.5747^O N and 77.6798^O E respectively. It consisted of a UV-coated double-layered polycarbonate sheet bent in parabolic shape to obtain solar energy more efficiently. It

was used to absorb the solar radiation inside the drying chamber. The polycarbonate sheet is durable and offers 60% better thermal insulation than glass. The UV coating was essential to protect the underlying material from harmful radiation. The parabolic polycarbonate sheet was attached to aluminium supports. The base of the polycarbonate sheet was a Cudappah Black Stone slab. It was used to resist the heat energy flow from PCM through the bottom of the stand. Rails were provided along the longitudinal length of the stand for the movement of the chamber base. A stand made of iron acted as the skeleton of the arrangement holding the drying chamber supported and positioned by four nylon wheels. The 12V, 10W Polycrystalline solar panel (PV Panel) was attached near the dehumidifier and was used to provide electrical energy to run the exhaust fan. An exhaust fan was used to evacuate the saturated air from the drying cavity and fill the chamber with fresh air from the atmosphere. It was operated automatically using sensor data, and it consumes power from the solar panel. The paraffin wax (PCM) was placed on the base of the stand and shielded with stainless steel. The humidity and temperature measurement device were placed within the dryer to record the temperature and humidity values. The nylon wheels on the bottom of the base helped in easier loading and unloading. The schematic representation is shown in the Figure 2.

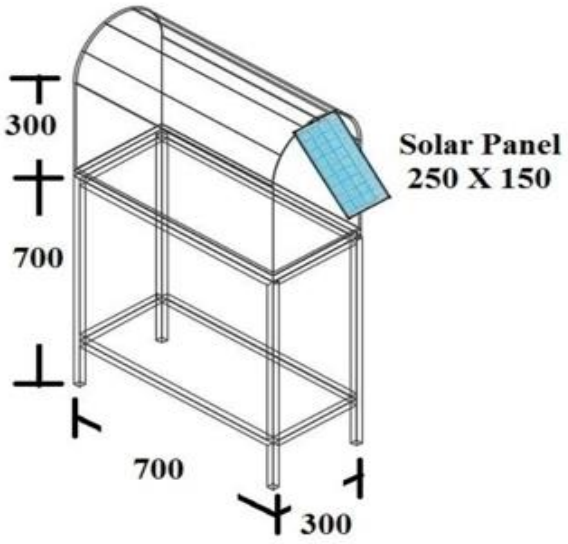

Figure 2: **Schematic representation of the solar dryer (3D view) (dimensions are in mm)**

Chapter 4: This chapter deals with the characterization studies for microencapsulated PCM. Scanning Electron Microscopy, FTIR Spectroscopy,

Differential Scanning Calorimetry, Thermogravimetric analysis were conducted to characterize the PCM.

FOURIER TRANSFORM INFRARED SPECTROSCOPY (FTIR)

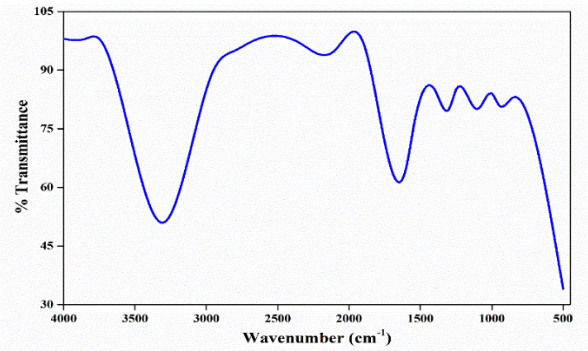

Figure 3 FTIR peaks for paraffin microcapsules.

The Figure 3 shows the FTIR spectrum for paraffin microcapsule. For pure paraffin the vibration occurred at 3325.76 cm^{-1} due to the stretching frequency of O-H. Similar peaks happened at 2925.25 cm^{-1} and 2845.64 cm^{-1} due to the stretching frequency of CH_3, CH_2 and C-H functional group. Peaks at 1645.31 cm^{-1} and 1542.35 cm^{-1} are also predicted to C=C stretch. Peaks were obtained in the finger point region (1500-500 cm^{-1}) at 1364.21 cm^{-1} and 1012.27 cm^{-1} caused by bending vibration of the CH_3, CH_2 and C-H functional groups.

The FT-IR result concluded the absence of new peaks that all of the microcapsules synthesised had no chemical interaction between nanoparticle and shell material and only physical interaction, implying that the addition of nanoparticles had no effect on the properties of pure encapsulated paraffin. So, it was used for the long-term usage for TES system.

DIFFERENTIAL SCANNING CALORIMETRY (DSC)

The Figure 4 show that the double endothermic melting and double exothermic solidification peaks occurred. A first peak can be attributed to a solid-solid transition, whereas the second and major peak is attributed to a solid-liquid transition. The solid-solid transition is defined as the phase transition from an ordered to a more disordered phase. The melting onset temperature is 45.5 °C and freezing onset temperature is 57 °C. the heat of fusion is 184.48 kJ/kg. There is no chemical reaction between shell and

a core material because the phase change performance and all of them present a single fusion and crystallization peaks.

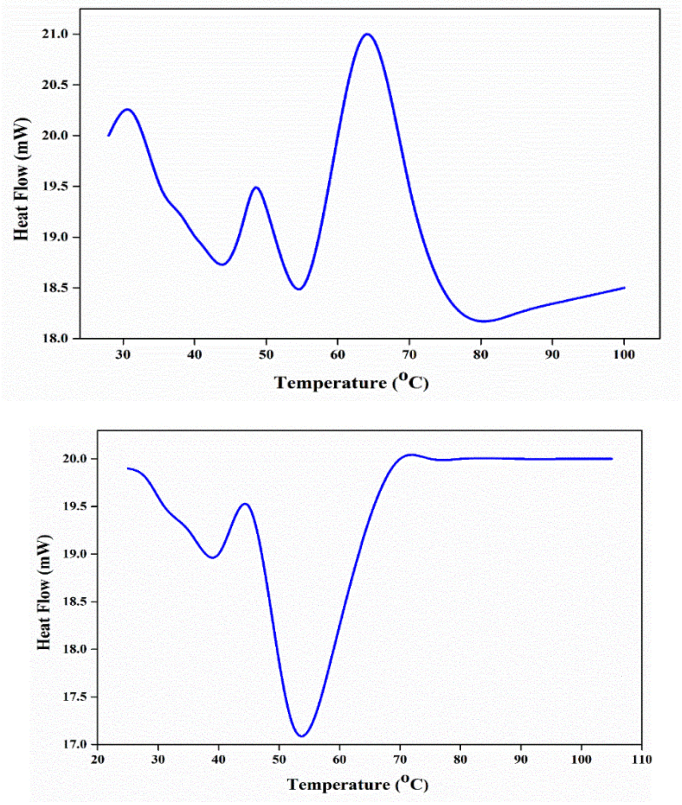

Figure 4 (a) Heating curve of microcapsules and 4 (b) Cooling curve of microcapsules.

THERMOGRAVIMETRIC ANALYSIS

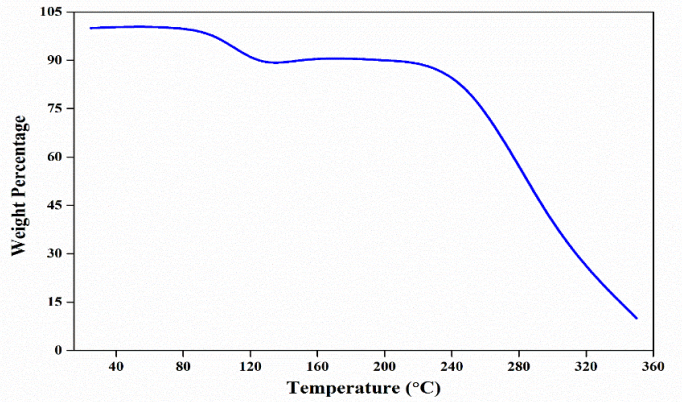

Figure 5 TGA curve for microencapsulated PCM

Thermal stability is important when using the PCM in heat storage applications because it indicates the decomposition temperature of the PCM. The TGA method is used to measure the material weight in a function of time or temperature in a

controlled condition. Figure 5 show that the pure paraffin was decomposed at 238 ℃ and the weight loss begins at 156 ℃ and 240 ℃ nearly all the paraffin wax got evaporated. Water is more common in samples with a lower paraffin loading ratio, as evidenced by TGA curves that show a weight decrease at nearly 130 °C for all samples, and evaporation of adsorbed water molecules. The first curve will occur closely at 228 °C there the leakage will occur through the cracked shell. When the temperature reaches 350 °C large amount of weight loss will be happened.

Chapter 5: This chapter describes the study of coconut drying and explains the average, peak temperature and drying duration. Also, discussed the weight and temperature analysis.

Organic paraffin wax, PCM with a melting temperature of 60 ℃, was used in the solar dryer. The drying performance and characteristics were analysed for different drying methods based on the moisture removed, drying time, and sensory attributes of the samples. In addition, a comparative evaluation of drying time, drying rate, peak temperature, and the average temperature inside and outside the drying chamber for coconut in the proposed solar dryer's system was conducted.

The outcome of PCM in the solar dryer on the drying experience can be assessed based on the ability of the setup to continue a uniformly high temperature in the chamber. Naturally, the chamber temperature reaches a maximum level, i.e., peak temperature, during the time of severe solar exposure. i.e., solar noon. While the period is comparatively short, the high temperature during that period favours a higher drying rate. But, the benefit of using PCM in the solar dryer is that the total drying time is reduced by continuing the required temperature in the chamber. A food product is claimed to be maximumly dried if the weight remains constant consecutively for at least 3-5 measurements. the average temperature continued in the drying chamber, and the peak temperature reached in the chamber for different drying conditions with and without PCM. Paraffin wax starts to melt above 45-50 ℃, and during the peak temperature (above 60 ℃), it entirely melts. However, the wax tends to solidify when the outside temperature decreases (below ~45 ℃). So, the phase transition happens within a smaller range of temperature, where the effect of PCM is observed.

The coconut was dried from an initial MC of 55.5% to a final MC of about 9%. the trend of weight changes over the total duration of drying of coconut for

different drying conditions. It can be observed that open sun drying of coconuts resulted in an inconsistent loss of weight throughout the drying duration. On the other hand, drying the coconuts using solar dryers (with and without PCM) resulted in a step-by-step loss of weight. A two-step process characterized the trend of weight loss for the dryer with 200 g of PCM, while the weight loss of the coconuts with 100 g and without PCM was noticed to have more than two steps, which were essentially observed in the peak solar exposure time of drying.

The drying time of the samples in different drying systems was distinct and reasonable based on the hypothesis of the study. The coconut samples had taken about 128 hours for complete drying, while solar drying took only about 120 hours. Up to 41% of drying time was reduced using PCMs in the solar dryers, wherein 100 and 200 g of PCM incorporated in the solar dryer set up decreased the absolute drying time to 100 and 76 hours, respectively. The drying time of coconut reduced by about 28 and 52 hours on using 100 and 200 g of PCM, correspondingly, compared to open sun drying.

Chapter 6: This chapter describes the study of grapes drying and explains the average, peak temperature and drying duration. Also, discussed the weight and temperature analysis.

In the PCM-equipped solar dryer, the effect of PCM can be estimated based on the consistency of the setup to continue uniformly high temperatures in the chamber during drying. In the drying chamber, the maximum temperature will be reached during the extreme solar exposure, irrespective of the PCM. During the period of exposure to high temperatures, the drying rate will be higher. But, the benefit of using PCM in the solar dryer is to reduce the entire drying time by continuing the minimum required chamber temperature. the average temperature continued in the drying chamber, and the peak temperature reached in the chamber for different drying conditions, namely open sun drying, solar drying without PCM, solar dryer with 100 and 200 grams of PCM. Paraffin wax starts to melt above 45-50 ℃, and in the peak temperature, it entirely melts as the peak temperature went above 58 ℃. But, when the outside temperature reduces, the wax tends to solidify below ~45 ℃. So, the phase transition happens between a smaller range of temperatures, where the effect of PCM is observed.

In the presence of PCM in the solar dryer, the average temperature was higher; nevertheless, the temperature was over the solidifying temperature of paraffin wax. In winters, the temperature may drop off considerably more, so the phase transition temperature range maybe more extended, so the heat storage and liberating limit of paraffin wax need to be significantly higher. In the summer, the average temperature of the chamber is effectively high to facilitate direct drying of the agro products.

The drying temperature inside the drying chamber was recorded periodically. The grapes were dried out from an initial MC of 80.2% to a final MC of about 18.6%. During open sun drying, the temperature was kept above 30 ℃ for more than 7 hours of solar exposure and above 40 ℃ for around 15 hours. In the evenings, the temperature drops on most of the days. Be that as it may, there is a steep fall in the temperature after the active sunshine hours in all the drying methods. During the drying of grapes in the solar dryer, the temperature was kept above 40 ℃ for more than 6 hours, especially during solar exposure and above 50 ℃ for around 5 hours or more than 60 ℃ was attained over 2 hours. A higher temperature was maintained in the solar dryer related to that of open sun drying. In the solar dryer with 100 grams of PCM, the temperature was above 35 ℃ for more than 5 hours of solar exposure, and more than 50 ℃ for 5 hours, and above 60℃for about around 3 hours. In the solar dryer with 200 grams of PCM, the temperature was kept up above 50 ℃ for more than 4 hours of solar exposure, and more than 60 ℃ was retained for about 3 hours. The PCM had influenced the temperature to remain reasonably high all through the drying period.

The weight measurements taken for the grapes dried using different conditions. The weight loss is a direct indication of the removal of moisture from the grapes. If the quantity of PCM increases, the capacity of storing and releasing a huge quantity of latent heat during the phase transition period can be maximum exploited. Of all the methods, the solar dryer with 200 grams of PCM exhibited the best performance (i.e., maximum weight loss) by completing the drying process in about 10 hours. The smooth logarithmic reduction of the weight of the grapes can be observed for all the drying conditions. However, the presence of paraffin wax has compensated against the weight gain during the evenings, as observed from the weight trend using PCMs. In the absence of PCM, the grapes experienced the temperature and humidity impacts in the evening, which were not counteracted, resulting in fluctuating weight

measurements. Compared with open sun drying, the temperature will be higher inside the drying chamber in the other three methods. Due to maintaining the higher temperature in the solar dryer the drying time will be decreased.

During open sun dry the initial 10 hours saw a fall of the weight (higher drying rate), and after 12^{th}, 18^{th} and 36^{th} hour a little expansion in the weight was seen because of the moisture and temperature impacts after the evening. Contrast and open sun dry, the drying time will be decreased in the solar dryer. Since in the solar dryer the temperature will be higher in the solar dryer when contrast and open sun dry. In the open sun dry will needed up to 52 hours to dry the grapes absolutely anyway in the solar dryer will needed up to 34 hours to dry completely. In these two methods the solar dryer will lessen very nearly 18 hours of drying time.

Chapter 7: This chapter describes the study of chili drying and explains the average, peak temperature and drying duration. Also, discussed the weight and temperature analysis.

The drying performance of the various drying methods was compared using the sample's moisture and weight loss. Chili drying period, highest temperature, and average temperature were also noted. Chili drying in the open sun and chili drying with no PCM were used as control samples. The drying characteristics of the chili as well as the performance parameters of the dryer were compared between open sun dried and without PCM dried samples. The chili was left out in the open to dry in the sun. Every 1 hour, the weight was recorded. When the safe level of MC was reached, the drying process was terminated.

The average temperature that was kept in the drying chamber as well as the maximum temperature that was attained in the drying cavity with and without PCM. It depicts the temperature changes that occur throughout the drying of chili using various methods. Figure 7.1 shows on a regular basis, inside the drying cavity, the drying temperature was measured. The temperature was kept over 30 °C for also 16 hours and over 40 °C for around 3 hours during direct sun drying. The temperature drops in the evenings on most days. In all drying methods, the temperature drops precipitously after the effective sunlight hours. The solar dryer temperature was kept over 50 °C for around 8 hours, particularly in solar exposure, and over 60 °C for about 5 hours. In evaluation to open sun drying, the solar dryer without PCM

maintained a higher temperature. For over 6 hours of solar exposure, the solar dryer temperature with Macro PCM was more than 35 °C and 50 °C for 5 hours, and above 60 °C for about 4 hours. For greater than 3 hours of solar exposure, the solar dryer temperature with Micro PCM was had over 50 °C, and for about 4 hours, it was kept above 60 °C. Because of the PCM, the temperature remained relatively high throughout the drying period.

Chili was dried from an initial MC of roughly 72.5 % (w. b.), to a final MC of 10.0 % (w. b.). The weight measurements for the chili dry under various circumstances. The weight reduction is a straight result of moisture loss from the chili. The first 11 hours saw a sharp reduction in weight (higher drying rate), followed by a small rise in weight is detected in the direct sun dry. In the absence of PCM, the chili was subjected to temperature and humidity fluctuations after sunset, which were not compensated for, resulting in erratic weight measurements. The presence of paraffin wax can be seen to compensate for the variance in weight variation that occurs in the night-time, i.e. from 16 to 26 hours. The solar dryer with micro PCM performed the best (i.e., achieved the greatest weight loss) of all methods, finishing the drying process in about 52 hours. For all drying conditions, the weight of the chili decreases in a smooth logarithmic fashion. The presence of paraffin wax, on the other hand, has compensated for evening weight gain, as evidenced by the weight trend using PCMs. The drying chamber inside temperature is higher in the other three methods when compared with direct sun dry. The drying duration will be reduced because the solar dryer will maintain a higher temperature.

The weight of the chili dropped dramatically in the first 11 hours of drying in all of the drying processes. The curves exhibited distinct variations after the 11th hour, depending on the nature of drying. The quantitative analysis, of chili tend to continue unaffected as a result of drop at exact stages of drying, i.e., highest moisture elimination happens at specific drying times, and the samples weight reaches a stagnation state sooner than the open sun-dried samples or with solar dryers without PCM.

Chapter 8: This chapter describes the study of mango pulp drying and explains the average, peak temperature and drying duration. Also, discussed the weight and temperature analysis.

While using PCM in the solar dryer for the drying performance the inside dryer temperature will reaches high when compared without PCM in the solar dryer. During afternoon the chamber temperature will attain maximum level due to severe solar exposure. Higher drying rate will attain due to high temperature during the short period of time. The drying time will reduce by using the PCM in the solar dryer to continuing the essential temperature in the dryer. The food product weight will retain constant for more than 5-6 measurements, it is supposed to be dried. The peak temperature and average temperature attain in the drying chamber for various drying circumstances like Open sun dry, absence of PCM, with micro and macro PCM. Above 43 to 48 °C reaches the PCM begins to melt and fully melts at the peak temperature (above 56 °C). The PCM tends to solid when the outer temperature reaches lower 43 °C. As a consequence, the phase change arises in a lesser temperature range where the effect of PCM can be detected.

The drying duration, average and peak temperature for all the various method. Open sun dry has the drying duration of about 128 hours, average temperature of 29.7 °C and peak temperature of 41.3 °C. Using solar dryer, the drying duration will be reduced when compared with open sun dry. Peak temperature will be higher in the solar dryer and solar dryer with PCM when associated with open sun dry. comparing with grapes the mango dried time will be 5 times higher. Due to larger surface area convection heat transfer in the mango pulp is less compare to grapes. Hence the drying time of the mango increased 5 times.

The temperature variation for different method of drying mango pulp throughout the process. For open sun dry above 20 °C of temperature was continued for 10 hours, 30 °C was kept for 12 hours and above 40 °C was continued for 3 hours. In most of the days the temperature drop will occur on evening. Solar dryer without PCM above 30 °C of temperature was continued for 6 hours, above 40 °C was continued for 3 hours and above 50 °C was continued for 7 hours. Solar dryer with 100 gram of macro PCM has exceeding 30 °C of temperature was continued for 9 hours, above 50 °C was continued for 5 hours and above 60 °C was continued for 4 hours. In the solar dryer with 200 gram of macro PCM exceeding 50 °C of temperature was continued for 5 hours and above 60 °C was continued for 6 hours. Solar dryer with 100 grams of micro PCM has exceeding 40 °C was continued for

7 hour and above 60 °C was continued for 6 hours. Solar dryer with 200 grams of micro PCM has above 40 °C was continued for 6 hour and above 60 °C was continued for 5 hours.

Chapter 9: In this chapter the conclusion of the research work and the scope for the future work are presented based on the results and discussion.

- In case of open sun dry, the drying duration for solar dryer without PCM, with 100g macro PCM, 200g macro PCM. The drying time duration reduced by 6%, 22% and 41% for drying coconut. About 8 hours of drying time was saved on drying the samples using conventional solar dryers rather than open sun drying.
- In case of open sun dry, the drying duration for solar dryer without PCM, with 100g macro PCM, 200g macro PCM. The drying time duration reduced by 35%, 58% and 81% for drying grapes.
- For drying grapes, compared with open sun drying, the conventional solar dryer reduced drying time by 18 hours. The solar dryer with PCM enabled a reduction in the drying time further by about 12-24 hours compared to the other methods
- In case of open sun dry, the drying duration for solar dryer without PCM, with 200g macro PCM, 200g micro PCM. The drying time duration reduced by 22%, 56% and 59% for drying chili.
- For drying chili, after 2.1 days of drying with the Micro PCM system. Solar dryer without PCM thermal storage during 4.2 days of drying. however, the MC of a comparable control sample10.0 percent (w.b.) was achieved after 5.3 days of drying in the direct sun dry method.
- In case of open sun dry, the drying duration for solar dryer without PCM, with 100g macro PCM, 200g macro PCM, 100g micro PCM, 200g micro PCM. The drying time duration reduced by 22%, 44%,50%, 56% and 63% for drying mango. By means of traditional solar dryers instead of open sun drying saved approximately 28 hours of drying time.

FUTURE WORK

- The large size of solar dryer to be prepared with increasing the quantity of PCM
- The quality changes like free fatty acids, peroxide value, rancidity, and subsequent shelf-life of the dried agro products can be evaluated
- The recovery of heat rejected from A/C condenser can be used to increase the performance of the solar dryer

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